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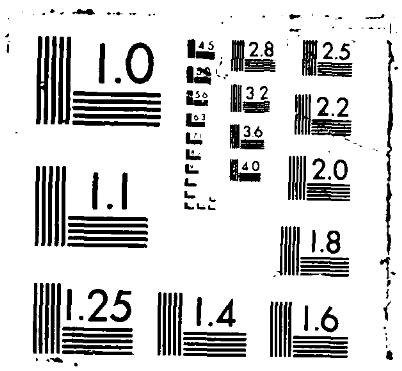
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MTL TR 87-59

# TEXTURE PROFILE IN THERMOMECHANICALLY PROCESSED 2-INCH-THICK 5 Ni-STEEL ARMOR PLATE

November 1987

HSUN HU
Battelle Columbus Laboratories
200 Park Drive, P.O. Box 12297
Research Triangle Park, NC 27709

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FINAL REPORT

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## ABSTRACT

The textural variation in the thickness direction of a 2-inch-thick 5 Ni-steel plate, produced by controlled hot-rolling to 90% reduction, immediately water-quenched, then tempered, has been studied. Besides the surface texture, which differs from the interior texture at midthickness only in intensity and in rotational displacement, there is a drastic change in the nature of the texture at the intermediate sections. An analysis of the deformation-zone geometry of the rolling passes indicates that the present observations are consistent with those reported for cold-drawn or cold-rolled strips. The usefulness of this particular texture for textured armor research and future armor development is discussed.

## CONTENTS

## INTRODUCTION

It has been known for more than 50 years that the crystallographic texture developed in the surface layers of a rolled metal sheet frequently differs from that of the interior of the sheet.[1,2] Depending on the metal and on the procedures of rolling, the surface texture may be different in the nature of the texture[3] or simply in the degree of symmetry with respect to the transverse direction as a rotational axis.[4] The frictional and shearing forces between the work-piece and rolls are considered to be responsible for the surface texture. It was shown by Tarnovskii et al.[5] that, under certain circumstances, the strain state in rolling is far from homogeneous. For example, a transverse vertical section may not remain planar and vertical as it passes through the roll gap. Within the zone of plastic deformation, the distortion may differ substantially from one layer to another in the thickness direction. This suggests that the texture may vary from layer to layer. Thus, across the thickness of the strip, there is a texture gradient or profile that may be developed in rolling deformation.

Using the parameter $\Delta = \bar{h}/L$, the ratio of the mean height of the deformation zone to its contact length (which is the reciprocal of the ratio used by Tarnovskii et al.[5]), Mathur and Backofen[6] showed a connection between $\Delta$ and the texture variation in cold-drawn aluminum-killed steel strips. When the parameter $\Delta$ is less than one, the texture is uniform through the thickness. As $\Delta$ becomes greater than one, a severe texture gradient appears. Similar observations were reported by Vandermeer and Bernal[7] in cold-rolled niobium strips.

The same principle should be applicable to plate rolling. Hence, a texture gradient or profile in the thickness direction of the plate would be expected. In hot-rolling, the method by which most plates are produced, the development of texture will, understandably, depend on temperature and other factors affecting recrystallization during hot deformation. For example, if the rolling temperature and the amount of strain are sufficiently high to cause recrystallization during or after each pass (or every few passes), then no texture or a very weak texture can be developed. When phase transformation occurs upon cooling the rolled plate, such as steels, the observed textures will have some specific relationship to the rolling textures of the parent phase austenite (e.g., the Kurdjumov-Sachs orientation). The thickness of the plate obviously has a significant influence on the texture heterogeneity in the thickness direction of the plate.

In 1982, a contract was awarded by AMMRC (Army Materials and Mechanics Research Center, now called the Materials Technology Laboratory, MTL) to the U.S. Steel Corporation for trial production on a full commercial scale of strongly textured

1. BARRETT, C.S. *Structure of Metals.* 2nd Ed., McGraw-Hill, New York, 1952, p. 464.
2. HU, H. *Texture of Metals.* Int. J. Texture, v. 1, 1974, p. 233.
3. VARGHA, G.V., and WASSERMANN, G. *Uber die Abhangigkeit der Kristallitanordnung in Gewalzten Aluminiumblechen von der Blechdicke.* Metallwirtschaft, v. 12, 1933, p. 511.
4. HU, H., SPERRY, P.R., and BECK, P.A. *Rolling Texture in Face-Centered Cubic Metals.* Trans. AIME, v. 194, 1952, p. 76.
5. TARNOVSKII, I. YA, POZDEYEV, A.A., and LYASHKOV, V.B. *Deformation of Metals During Rolling.* Translation, Pergamon Press, New York, 1965.
6. MATHUR, P.S., and BACKOFEN, W.A. *Mechanical Contributions to the Plane-Strain Deformation and Recrystallization Textures of Aluminum-Killed Steel.* Met. Trans., v. 4, 1973, p. 643.
7. VANDERMEER, R.A., and BERNAL, J.B. *Deformation Zone Geometry and Texture Gradients in Cold-Rolled Niobium.* Texture Cryst. Sol., v. 2, 1977, p. 183.

(112) + (111) armor plates. The thickness of the plates ranged from 2 inches to 3/16 of an inch. The project was successfully concluded in 1985.[8] Considering this extremely valuable milestone, i.e., the production of strongly textured plates in large thicknesses for the first time, the texture profile in the thickness direction of the 2-inch-thick plate is of great interest. The present report describes the details of such a study and the results obtained.

## MATERIAL AND PROCESSING

The 2-inch-thick plate used in the present study was the first successfully produced plate of such a heavy gage that had developed a strong (112) + (111) texture in the midthickness section of the plate. This plate was rolled from a 21 × 50 × 56 inch slab (No. 060735) that had been converted from the bottom portion of one of the ingots poured from the first 87-ton electric-furnace heat (Heat No. 4P0686).[9] The chemical composition of the steel is shown in Table 1, and the detailed rolling schedule is shown in Table 2.

Table 1. CHEMICAL COMPOSITION OF ARMOR STEEL FOR THE PRODUCTION OF TWO-INCH-THICK PLATES OF TEXTURED ARMOR[9] (LADLE ANALYSIS HEAT NO. 4P0686*)

| Sample Location** | Chemical Composition (wt%) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | Mn | P | S | Si | Cu | Ni | Cr | Mo | V | Total Al | Ce | Sn |
| 1st Ingot | 0.40 | 0.58 | 0.006 | 0.005 | 1.24 | 0.97 | 5.43 | 0.11 | 0.46 | 0.08 | 0.036 | 0.018 | 0.004 |
| 4th Ingot | 0.40 | 0.58 | 0.006 | 0.004 | 1.23 | 0.97 | 5.43 | 0.11 | 0.46 | 0.08 | 0.035 | 0.018 | 0.005 |

*National-Duquesne Works electric-furnace heat melted June 30, 1982.
**Lollypop sample taken from top of the indicated ingot after teeming.

After reheating and soaking at 1600°F, the slab was rolled to 20 × 50 × 58 in. It was then turned 90 degrees for continued rolling to a final thickness of 2 in. Immediately following the final pass, the plate was on-line quenched to below ~200°F and tempered in a continuous annealing furnace at ~390°F for 90 min. The overall dimensions of the plate were approximately 2 × 60 × 500 in. A slight widening (from 58 to 60 in.) had obviously occurred in the plate after 90% reduction in thickness.

A 3-in. long by plate-width piece was cut at the mid-length position of the plate. This was used as the sample material for various metallurgical examinations and measurements.

## METHOD OF EXAMINATION

The crystallographic texture of the plate was examined by determining the pole figures from two families of crystallographic planes, namely {110} and {200}, using X-ray diffraction. In conjunction with a Siemens texture goniometer, the $ZrO_2$-filtered $MoK_{\alpha}$ radiation, operated at 50 kV and 20 mA, and a scintillation counter with a pulse-height discriminator were used for texture measurements. Employing the

8. MANGANELLO, S.J., HU, H., and JIM, G.A. *Limited Production of Special Armor Steel for Combat Vehicles.* AMMRC Final Report TR 85-13, Contract No. DAAG46-82-C-0029, June 1985.
9. HU, H., and BAUMGARTEN, W.J., Jr. *Limited Production of Special Armor Steel for Combat Vehicles.* AMMRC Quarterly Report No. 1, Contract No. DAAG46-82-C-0029, July 1982.

Table 2. HOT ROLLING CONDITIONS, SLAB NO. 060735[9] (ROLLED 11/30/82)

| Pass No. | Roll Setting (in.) | Reduction (in.) | Reduction (%) | Separating Force ($10^6$ lb) | Surface Temp ($^\circ F$) Entry | Surface Temp ($^\circ F$) Exit |
|---|---|---|---|---|---|---|
| 0 | 21.00 | 0 | 0 | - | - | - |
| 1 | 20.50 | 0.50 | 2.4 | 0.5 | 1350 | - |
| 2 | 20.00 | 0.50 | 2.4 | 4.4 | - | - |
| 3 | 19.50 | 0.50 | 2.5 | 9.6 | 1320 | - |
| 4 | 19.02 | 0.48 | 2.5 | 10.5 | - | - |
| 5 | 18.50 | 0.52 | 2.7 | 8.0 | 1330 | - |
| 6 | 17.97 | 0.53 | 2.9 | 10.7 | - | - |
| 7 | 17.50 | 0.47 | 2.6 | 10.7 | 1340 | - |
| 8 | 16.97 | 0.53 | 3.0 | 10.9 | - | - |
| 9 | 16.50 | 0.47 | 3.2 | 10.4 | 1308 | - |
| 10 | 16.00 | 0.50 | 3.0 | 11.8 | - | 1360 |
| 11 | 15.50 | 0.50 | 3.0 | 10.8 | 1378 | - |
| 12 DW | 14.93 | 0.57 | 3.7 | 12.0 | - | - |
| 13 | 14.50 | 0.43 | 2.9 | 11.1 | 1330 | - |
| 14 | 13.97 | 0.53 | 3.7 | 11.4 | - | - |
| 15 | 13.50 | 0.47 | 3.4 | 11.0 | 1370 | - |
| 16 | 13.00 | 0.50 | 3.7 | 10.9 | - | 1409 |
| 17 | 12.75 | 0.25 | 1.9 | 10.3 | 1380 | - |
| 18 | 12.38 | 0.37 | 2.9 | 9.8 | - | 1450 |
| 19 | 12.00 | 0.38 | 3.1 | 10.1 | 1397 | - |
| 20 | 11.63 | 0.37 | 3.1 | 9.2 | - | 1441 |
| 21 | 11.25 | 0.38 | 3.3 | 9.8 | 1410 | - |
| 22 | 10.88 | 0.37 | 3.3 | 9.2 | - | 1451 |
| 23 | 10.50 | 0.38 | 3.5 | 9.5 | 1430 | - |
| 24 | 10.25 | 0.25 | 2.4 | 8.5 | - | 1451 |
| 25 | 9.97 | 0.28 | 2.7 | 8.5 | 1440 | - |
| 26 | 9.40 | 0.57 | 5.7 | 7.5 | - | 1481 |
| 27 | 8.88 | 0.52 | 5.5 | 8.6 | 1430 | - |
| 28 | 8.30 | 0.58 | 6.5 | 8.7 | - | 1493 |
| 29 | 7.80 | 0.50 | 6.0 | 8.8 | 1460 | - |
| 30 | 7.80 | 0 | 0 | 7.5 | 63 sec - * | 1510 |
| 31 RW | 7.80 | 0 | 0 | 5.0 | 1520 | - |
| 32 RW | 7.38 | 0.42 | 5.4 | 4.0 | 34 sec - * | - |
| 33 | 6.95 | 0.43 | 5.8 | 7.2 | 1460 | - |
| 34 | 6.50 | 0.45 | 6.5 | 7.8 | - | 1420 |
| 35 | 6.09 | 0.41 | 6.3 | 7.5 | 1445 | - |
| 36 | 6.10 | 0 | 0 | 6.5 | 31 sec - * | 1460 |
| 37 DW | 6.10 | 0 | 0 | 4.5 | 1460 | - |
| 38 DW | 6.10 | 0 | 0 | 3.5 | - | - |
| 39 | 5.75 | 0.35 | 5.7 | 6.0 | 1400 | - |
| 40 | 5.38 | 0.37 | 6.4 | 6.5 | - | 1380 |
| 41 | 5.05 | 0.33 | 6.1 | 6.8 | 1425 | - |
| 42 | 4.75 | 0.30 | 5.9 | 6.0 | 54 sec - * | 1450 |
| 43 | 4.75 | 0 | 0 | 3.8 | 1450 | - |
| 44 | 4.75 | 0 | 0 | 3.0 | - | 1390 |
| 45 | 4.45 | 0.30 | 6.3 | 5.4 | 1410 | - |
| 46 | 4.20 | 0.25 | 5.6 | 5.2 | - | 1440 |
| 47 | 3.93 | 0.27 | 6.4 | 5.6 | 1430 | - |
| 48 | 3.70 | 0.23 | 5.9 | 5.2 | - | 1440 |
| 49 | 3.45 | 0.25 | 6.8 | 5.6 | 1445 | - |
| 50 | 3.25 | 0.20 | 5.8 | 4.8 | 28 sec - * | 1450 |
| 51 DW | 3.25 | 0 | 0 | 3.4 | 1460 | - |
| 52 | 3.25 | 0 | 0 | 2.5 | - | 1370 |
| 53 | 3.05 | 0.20 | 6.2 | 4.3 | 1405 | - |
| 54 | 2.88 | 0.17 | 5.6 | 4.5 | - | 1420 |
| 55 | 2.63 | 0.25 | 8.7 | 4.8 | 1430 | - |
| 56 | 2.50 | 0.13 | 4.9 | 4.2 | - | 1430 |
| 57 | 2.38 | 0.12 | 4.8 | 4.3 | 1420 | - |
| 58 | 2.22 | 0.16 | 6.7 | 4.0 | - | 1426 |
| 59 | 2.10 | 0.12 | 5.4 | 3.9 | 1430 | - |
| 60 | 2.10 | 0 | 0 | 2.7 | - | 1440 |
| 61 | 2.07 | 0.03 | 1.4 | 2.4 | 1430 | - |
| 62 | 2.04 | 0.03 | 1.4 | 2.4 | - | 1425 |
| 63 | 2.02 | 0.02 | 1.0 | 2.3 | 1410 | - |
| 64 | 2.02 | 0 | 0 | 2.2 | - | 1390 |
| | | | | | 1380 to Quenching | |

*Hold to cool.
DW = Descale Water
RW = Roll Water

Schulz reflection method,[10] pole-figure measurements were made from 0 to 80 degrees in the tilting angle. The measured intensity data were then corrected, computed, and plotted automatically into pole figures, with intensity levels expressed in units of a random iron powder specimen.

Figure 1 is a schematic illustration showing thickness levels (as indicated on the left in fraction of plate thickness) and distance below the rolling surface (as indicated on the right in inches) at which the texture of the plate was measured. The microstructure and the hardness of the plate had been examined previously.[9] That the plate was hardened completely through its thickness by quenching is indicated by the hardness values shown in Table 3. Complete hardening was also supported by the microstructure of the plate. From surface to midthickness, the microstructure was entirely martensitic. All these examinations and measurements were conducted over only one-half thickness of the plate. It was assumed that the features in the other half were essentially similar.

Table 3. HARDNESS OF QUENCHED AND TEMPERED PLATE NO. 060735 (FOURTH 2-INCH-THICK PLATE OF TEXTURED ARMOR)[9]

| Distance Below Surface (mm) | Diamond Pyramid Hardness Number | $R_C$ Hardness Number |
|---|---|---|
| 0.5 | 602 | 55.3 |
| 2 | 618 | 56.2 |
| 4 | 618 | 56.2 |
| 6 | 614 | 55.9 |
| 8 | 606 | 55.5 |
| 10 | 610 | 55.7 |
| 12 | 598 | 55.1 |
| 14 | 579 | 54.1 |
| 16 | 590 | 54.7 |
| 18 | 586 | 54.5 |
| 20 | 586 | 54.5 |
| 22 | 575 | 53.9 |
| 24 | 575 | 53.9 |
| 26 | 586 | 54.5 |
| | Average | 55.0 |

Preparation of the specimens for texture measurements was accomplished as follows: First, a piece of the sample material was cut ~ 1 1/4 × 1 1/4-in. in area and by the thickness of the plate. The piece was again cut at the midthickness section. Using the rolling surface as reference plane, the midthickness section plane was gound parallel to the rolling surface and to exactly half thickness of the plate. Specimens of the intermediate sections, as shown in Figure 1, were then cut and ground to the thickness level desired. To remove the distorted material on the sectioned plane, metallographic polishing to the exact thickness level was employed, followed by a light chemical etching. X-ray diffraction was taken from this distortion-free face of the specimen.

Besides the {110} and {200} pole figures, measurements of the integrated peak intensities of five reflections from the rolling plane of these specimens were also obtained. The variation of these peak intensities across the thickness of the plate

10. SCHULZ, L.G. *A Direct Method of Determining Preferred Orientation of a Flat Reflection Sample Using a Geiger Counter X-Ray Spectrometer.* J. Appl. Phys., v. 20, 1949, p. 1030.

provides a more direct representation of the texture profile than do the pole figures. These peak intensity measurements, however, do not provide information on the directions of the crystallites in the plate; they represent the relative population densities of those specific planes lying parallel with the rolling plane of the plate.

## RESULTS AND DISCUSSION

Figures 2a and 2b are the (110) and (200) pole figures, respectively, showing the texture of the plate at the midthickness section. The texture is the familiar (112) + (111) type, that was used previously to describe the texture observed in the straight-away rolled and on-line quenched steel armor plates. As indicated in the legend of the pole figures, the texture is {112} <110> and 13°~{111} <112>. The latter can be more closely described as 3° ~ {332} <113>; the use of the lower indices, {111} instead of {332}, was solely for the purpose of simplification in description. The texture of the plate at the 3/8 T section (0.75 in. below the rolling surface) was essentially same, namely, a strong (112) + (111) texture, as shown in Figures 3a and 3b.

At the 1/4 T section (0.50 in. below the rolling surface) of the plate, the texture observed was completely different from that at or near the midthickness section. The texture can be described as a strong (110) + (100) type, as shown in Figures 4a and 4b for the (110) and (200) pole figures, respectively. The same kind of texture, but at a substantially weaker intensity, was observed at the 1/8 T section (Figures 5a and 5b).

At sections still closer to the rolling surface, e.g., 1/16 T and 1/18 T (0.15 in. and 0.11 in. below the plate surface), the texture was a combination of relatively weak {112} <110> plus {111} <112> with decreasing intensity toward the surface. This is shown by the (110) pole figure determined from the 1/16 T section of the plate (Figure 6), and by the (200) pole figure determined from the 1/18 T section of the plate (Figure 7). Even closer to the rolling surface, the decarburized layers, oxide scales, and surface irregularities made texture determinations hardly worthwhile for the present investigation.

A summary of the texture profile in the 2-inch-thick armor plate, based on the results obtained from these pole figures, is given in Table 4. The observation of a strong (110) + (100) type texture in the 1/4 T to 1/8 T sections is of particular interest from both academic and practical considerations. These will be discussed in more detail later in the text.

Results from integrated peak intensity measurements at the various sections are presented in Figure 8. Five important reflections of low-index planes, namely (110), (200), (211), (310), and (222), were used. The strong (110) + (100) texture observed at the 1/4 to 1/8 T sections of the plate from the pole figures was substantiated by this peak-intensity profile shown in Figure 8. As can be noted in this plot, the intensities of the (211) and (222) reflections at the midthickness section were not outstandingly high. This can be understood on the basis that the ideal orientations best describing the observed texture are {112} <110> plus 3° ~{332} <113>, the latter being 13° ~ {111} <112>. Hence, the observed (112) and (222) intensities from the peak intensity measurements actually corresponded to areas that were off the exact positions of the intensity maxima on the pole figures.

Table 4. SUMMARY OF TEXTURE PROFILE IN THE 2-INCH-THICK ARMOR PLATE

| Section Position | | | |
|---|---|---|---|
| Fraction of Plate Thickness | Distance Below Rolling Surface | Pole Figures Shown | Features of Texture |
| 1/2 T | 1.00 in. | (110)<br>(200) | texture similar |
| 3/8 T | 0.75 in. | (110)<br>(200) | strong (112) + (111) type |
| 1/4 T | 0.50 in. | (110)<br>(200) | strong (110) + (100) type |
| 1/8 T | 0.25 in. | (110)<br>(200) | weak (110) + (100) type |
| 1/16 T | 0.15 in. | (110) | texture similar |
| 1/18 T | 0.11 in. | (200) | weak {110} <110> + {111} <112> type |

According to Mathur and Backofen,[6] in strip drawing or rolling, the development of texture gradients or heterogeneity occurs when the parameter $\Delta = \bar{h}/L$ is greater than one. In cold strip rolling, $\Delta$ tends to lie near one, because a horizontally directed friction force large enough for the rolls to 'bite' and deliver well-lubricated strip cannot usually be developed with $\Delta$ much larger than unity. By deliberately controlling the parameter $\Delta$ to be greater than one during rolling, Vandermeer and Bernal[7] were able to show that severe texture gradients developed in cold-rolled niobium strips. In hot-rolling, the frictional forces between the roll and the work piece is undoubtedly considerably higher than in well-lubricated cold strip rolling. From the roll settings, which were approximately the slab thicknesses at each pass, and the percentage of reduction for each pass, as listed in Table 2, the parameter $\Delta$ can be calculated readily by the equation,[9]

$$\Delta = \frac{\bar{h}}{L} = \sqrt{\frac{h_o}{4Rr}}\,(2 - r) \quad , \tag{1}$$

where $\bar{h}$ is the mean height of the deformation zone, L is the contact length between the roll and the work piece, $h_o$ is the entering thickness of the plate, R is roll radius,* and r is the fraction of reduction of each pass.

Thus, at the beginning of straight-away rolling, i.e., pass No. 2, $h_o$ is 20.00 inches, r is 0.025, and the radius of rolls, R, is 38.50/2 = 19.25 inches; hence,

$$\Delta = \sqrt{\frac{20}{4 \times 19.25 \times 0.025}}\,(2 - 0.025)$$

$$= 6.37$$

*The roll diameter of the Homestead 160-in. mill is 38.5 inches.

From such calculations, the values of Δ were obtained for a number of individual passes employed in rolling the 2-inch-thick plate. These are presented in Table 5. As shown by this tabulation, the Δ values were all greater than one, and were particularly much greater than one when the thickness of the plate was large. When the reduction was small (such as in pass No. 62), a large Δ value was observed even when the plate thickness was reduced significantly to the finishing gages. In fact, Eq. (I) indicates that, for a more homogeneous texture profile (i.e., a smaller Δ value), a smaller initial thickness of the plate, a larger roll diameter, and a heavier reduction per pass are desired.

Table 5. THE DEFORMATION-ZONE GEOMETRY PARAMETER, Δ, OF SELECTED PASSES DURING ROLLING OF THE 2-INCH-THICK ARMOR PLATE

| Pass No. | Entering Thickness (in.) | Thickness Reduction (%) | Deformation-Zone Parameter Δ |
|---|---|---|---|
| 2 | 20.00 | 2.5 | 6.37 |
| 7 | 17.50 | 3.0 | 5.42 |
| 11 | 15.50 | 3.7 | 4.58 |
| 15 | 13.50 | 3.7 | 4.27 |
| 19 | 12.00 | 3.1 | 4.41 |
| 23 | 10.50 | 2.4 | 4.71 |
| 26 | 9.40 | 5.5 | 2.90 |
| 32 | 7.38 | 5.8 | 2.50 |
| 34 | 6.50 | 6.3 | 2.24 |
| 40 | 5.38 | 6.1 | 2.08 |
| 45 | 4.45 | 5.6 | 1.97 |
| 49 | 3.45 | 5.8 | 1.71 |
| 54 | 2.88 | 8.7 | 1.25 |
| 56 | 2.50 | 4.8 | 1.61 |
| 58 | 2.22 | 5.4 | 1.42 |
| 62 | 2.04 | 1.0 | 3.24 |

The high Δ values in rolling the 2-inch-thick plate and the observation of a drastic change in the nature of the texture in the thickness direction are consistent with the results for cold strip rolling by Vandermeer and Bernal.[7] The textures observed near the surface of the plate were a combination of {112} <110> plus {111} <112> with relatively weak intensities. These textures are similar in nature to the interior textures observed at 1/2 T and 3/8 T sections, but deviated by rotations about the transverse direction. Surface textures of such nature are produced by frictional and shearing forces parallel to the rolling plane. Hence, the observed textures were to be expected.

The formation of a strong (110) + (100) type texture at 1/4 T to 1/8 T sections in the 2-inch-thick plate is not only interesting for academic considerations, but also valuable in textured-armor research. It was shown in the initial studies of the effect of texture on the ballistic properties of steel armor[11] that, by controlled thermomechanical processing, three different kinds of textures could be produced in the quenched-and-tempered plates. These were the (112) + (111) type, the (110) + (100) type, and the (111) type. Among the three, only the (112) + (111) type was produced with very high intensity. The (110) + (100) type texture was produced by quenching the recrystallized austenite with cube texture. Because of its low texture intensity (~2 times random), the ballistic limit was approximately the same as that of a random plate. There has been no opportunity to test the effect of this type of texture on the ballistic property.

11. HU, H., SPEICH, G.R., and MILLER, R.L. *Effect of Crystallographic Texture, Retained Austenite, and Austenite Grain Size on the Mechanical and Ballistic Properties of Steel Armor Plates.* AMMRC TR 76-22, Contract No. DAAG46-75-C-0094, July 1976.

The formation of a strong (110) + (100) type* texture (~6 times random) over ~0.25-inch-thick material in the 2-inch-thick plate provides the opportunity of testing such textured plate ballistically by cutting or grinding out this section from the 2-inch plate. Such information should be of scientific as well as practical interest.

## SUMMARY AND CONCLUSIONS

1. The textural variation in the thickness direction of a 2-inch-thick, 5 Ni-steel armor plate has been studied. The plate was produced by controlled hot-rolling in the standard manner to 90% reduction in thickness, and on-line quenched to a completely martensitic structure, then tempered for the desired hardness through the thickness of the plate.

2. The textures of the plate at various thickness levels, from slightly below the rolling surface to the midthickness of the plate, were examined by X-ray pole figures and by the integrated peak intensities of a number of important reflections. The results from both examinations are consistent with each other, indicating that a drastic change in texture occurred in the sections from about 1/8 to 1/4 of the plate thickness.

3. The nature of the textures observed at the various thickness sections of the plate can be described as follows: At the 1/2 T and 3/8 T sections, the texture is essentially the same, namely, the familiar strong (112) + (111) type. It can be described more accurately as composed of strong {112} <110> and strong 13° ~ {111} <112>, or 3° ~ {332} <113>, orientations with a weak component of the {001} <110> orientation. At the 1/4 T to 1/8 T sections, the texture is similar but different in intensity, being stronger at the 1/4 T section. The texture can be described, for simplicity, as a (110) + (100) type. It consists of {110} <111> to {110} <112> plus {100} <001> orientations. At the 1/16 to 1/18 T sections, the texture is similar in nature but different in intensity, becoming weaker toward the surface. The texture can be described as composed of {112} <110> and {111} <112> orientations.

4. An analysis of the deformation-zone geometry during rolling of the 20-inch-thick slab to the 2-inch-thick plate indicates that the parameter $\Delta = \bar{h}/L$ (the mean thickness to contact-length ratio) was substantially greater than unity for most of the rolling passes. The present observation of a drastic change of texture in the thickness direction of the hot-rolled plate thus appears to be consistent with the observations reported in the literature for cold-drawn or cold-rolled strips. The texture observed near the surface layer of the plate was the kind of texture to be expected from the frictional and shearing forces parallel to the rolling plane.

5. The development of a strong (110) + (100) type texture over sections of considerable thickness (0.25 inch or more) in the 2-inch plate should be highly valuable to armor research and development in the future.

*Although classified as the same type as that in plates quenched from recrystallized austenite with cube texture, the directions of the planes are oriented differently. For the present 2-inch-thick plate, the (110) + (100) type texture refers to orientations from {110}<111> to {110}<112> plus {100}<001> (see Figures 4a and 4b). For the plates quenched from recrystallized austenite, the texture was {110}<001>, {110}<110>, and {001}<110>.[11]

## RECOMMENDATION FOR FUTURE WORK

During the initial study of the effect of texture on the mechanical and ballistic properties of the 5 Ni-steel armor plates,[11] a casual examination of the texture near the rolling surface and at approximately 1/4 T section of the 0.5-inch-thick plate having a strong (112) + (111) type texture was conducted. No drastic change of texture was observed. In view of present findings on the 2-inch-thick plate, a more detailed study of the texture profile, such as examinations at closer intervals so that changes in texture will not be bypassed, should be conducted for the 0.5-inch-thick plate. Also, the deformation-zone geometry for each individual pass in rolling should be examined.

## ACKNOWLEDGEMENTS

The writer wishes to express his sincere thanks to MTL for the funds provided through the program entitled "Armor Applications of Textured Materials" and to Battelle for arranging the Summer Faculty Research & Engineering Program that made this work possible. During this program, help from members of the Process Research Division of the Metals & Ceramics Laboratory, MTL, in particular G.H. Bishop and A. Zarkades, are gratefully acknowledged.

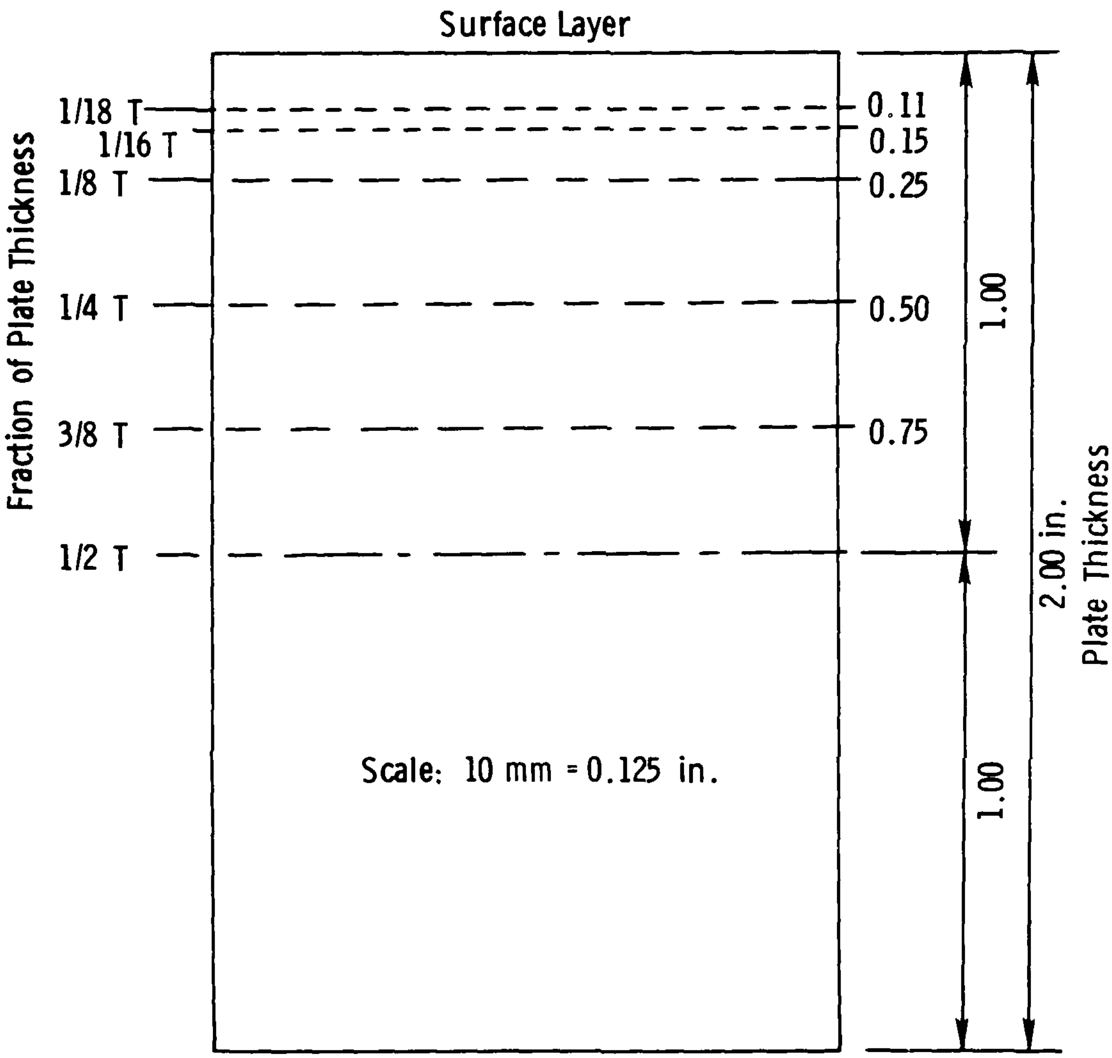


Figure 1. Schematic illustration showing thickness levels where texture of the plate was measured.

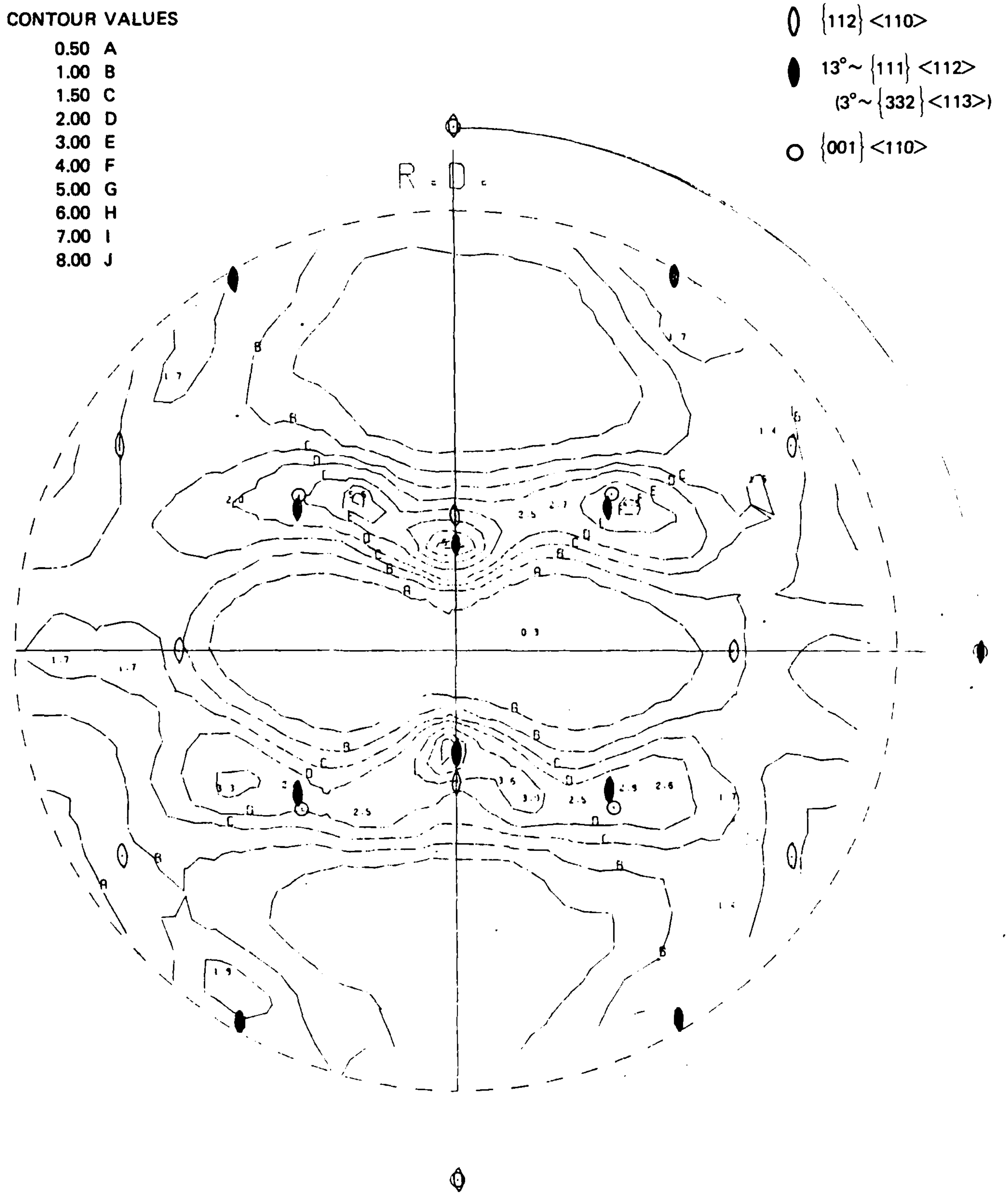


Figure 2a. The (110) pole figure showing texture of the 2-inch-thick plate at the midthickness (1/2 T) section. Dotted circle 80° from center of projection.

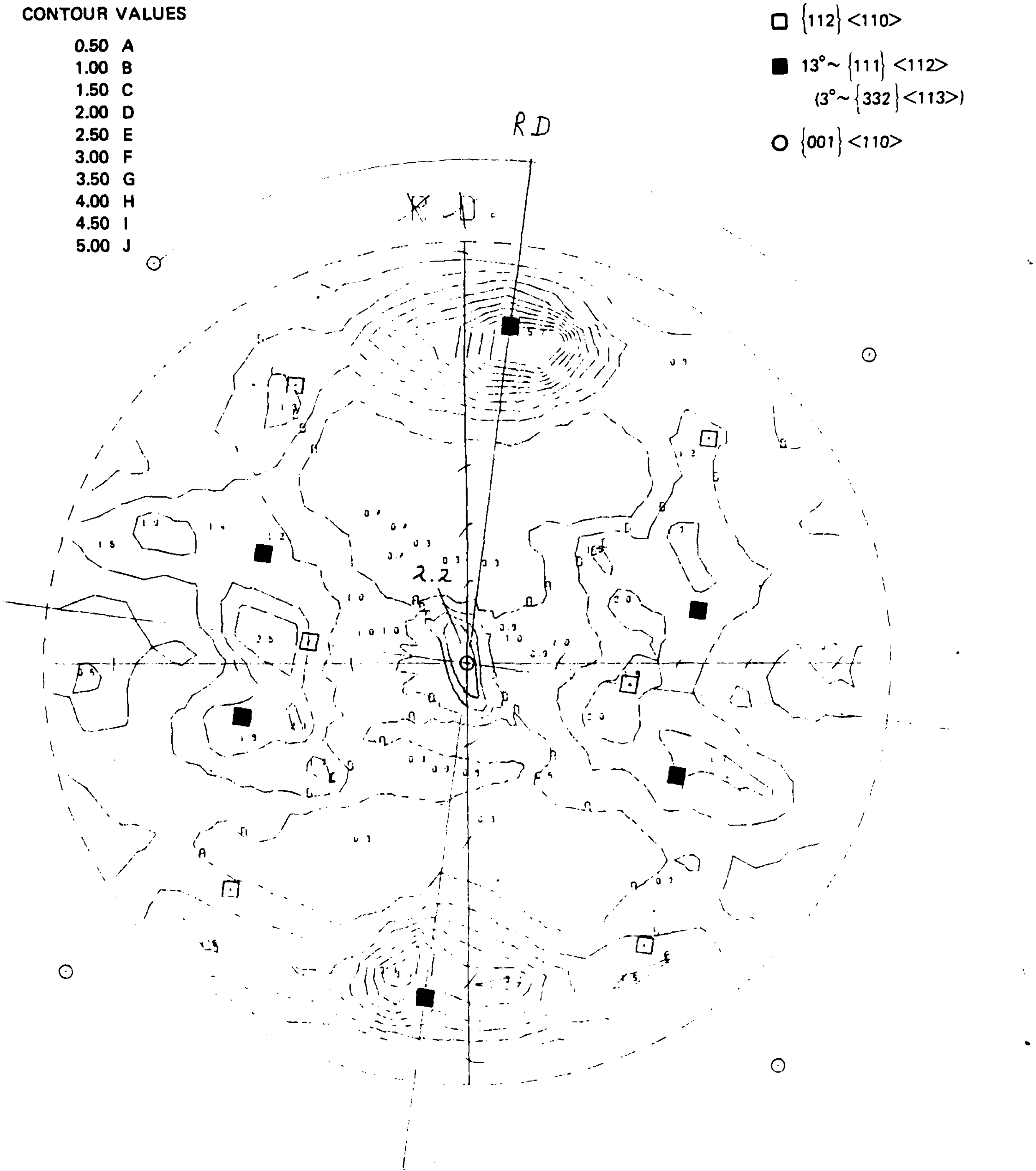


Figure 2b. The (200) pole figure showing texture of the 2-inch-thick plate at the midthickness (1/2 T) section. Dotted circle 80° from center of projection.

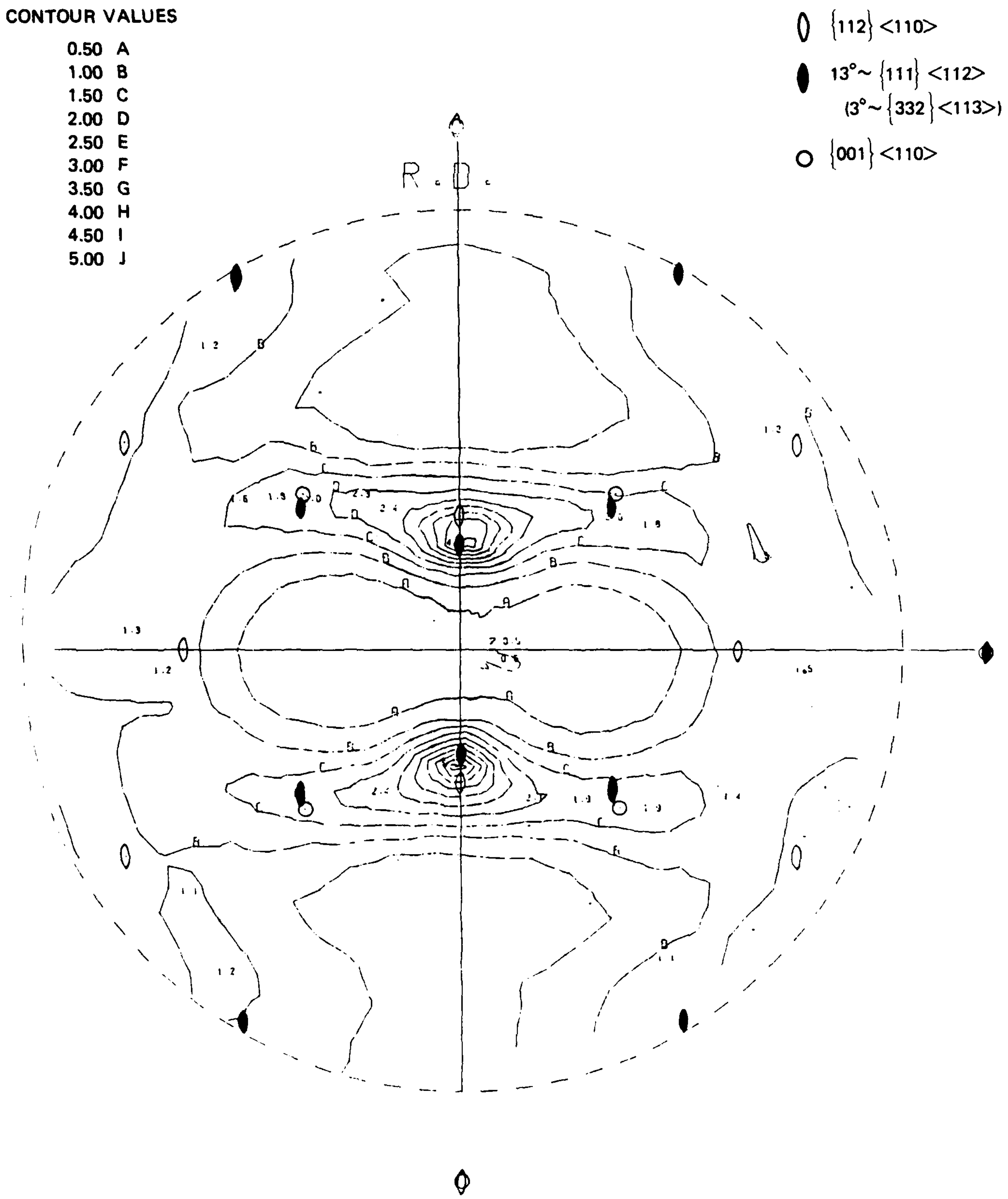


Figure 3a. The (110) pole figure showing texture of the 2-inch-thick plate at the 3/8 T section (0.75 in. below rolling surface). Dotted circle 80° from center of projection.

CONTOUR VALUES

0.50 A
1.00 B
1.50 C
2.00 D
2.50 E
3.00 F
3.50 G
4.00 H
4.50 I
5.00 J

□ {112} <110>

■ 13°~ {111} <112>
(3°~ {332} <113>)

○ {001} <110>

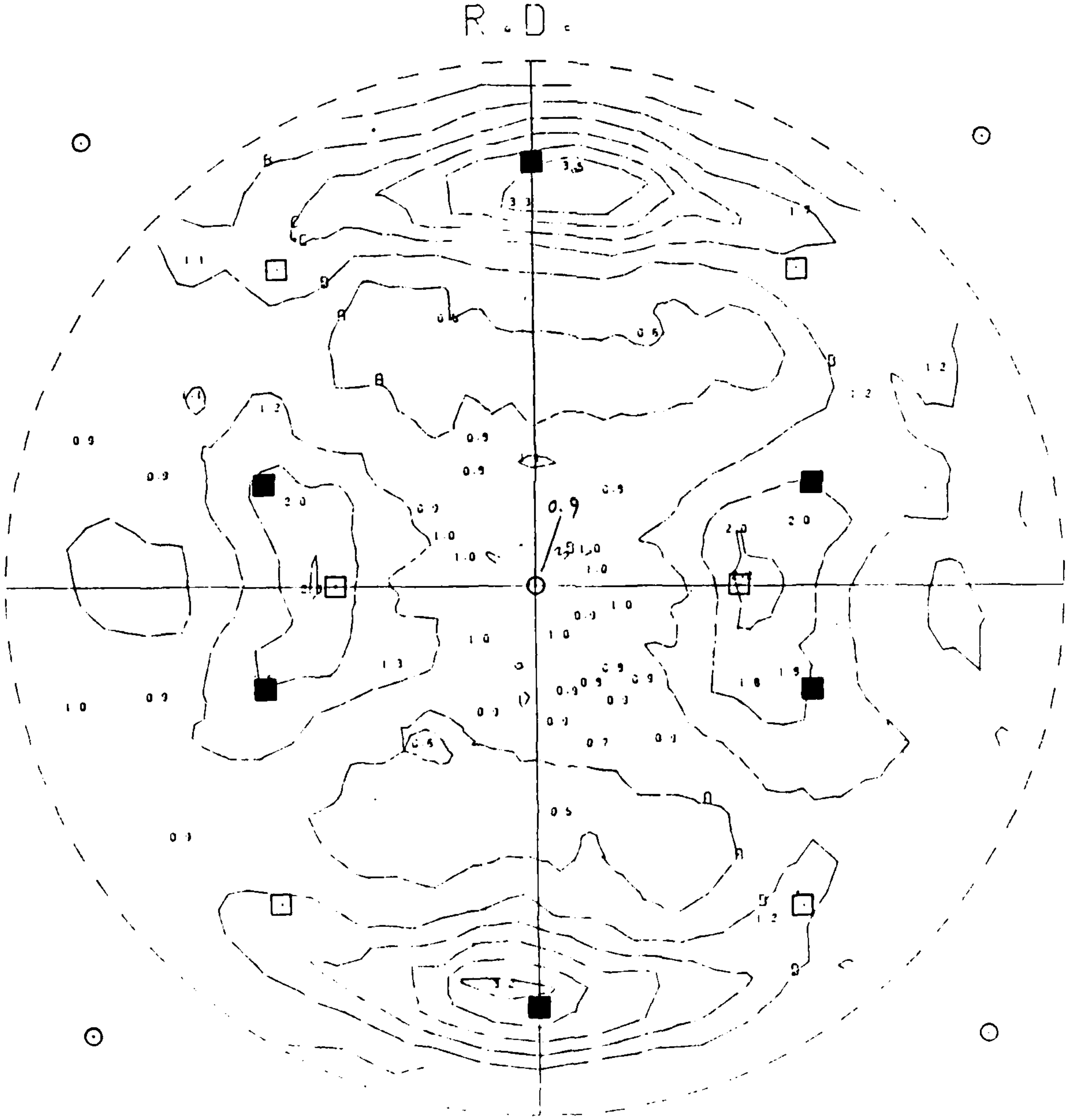


Figure 3b. The (200) pole figure showing texture of the 2-inch-thick plate at the 3/8 T section (0.75 in. below rolling surface). Dotted circle 80° from center of projection.

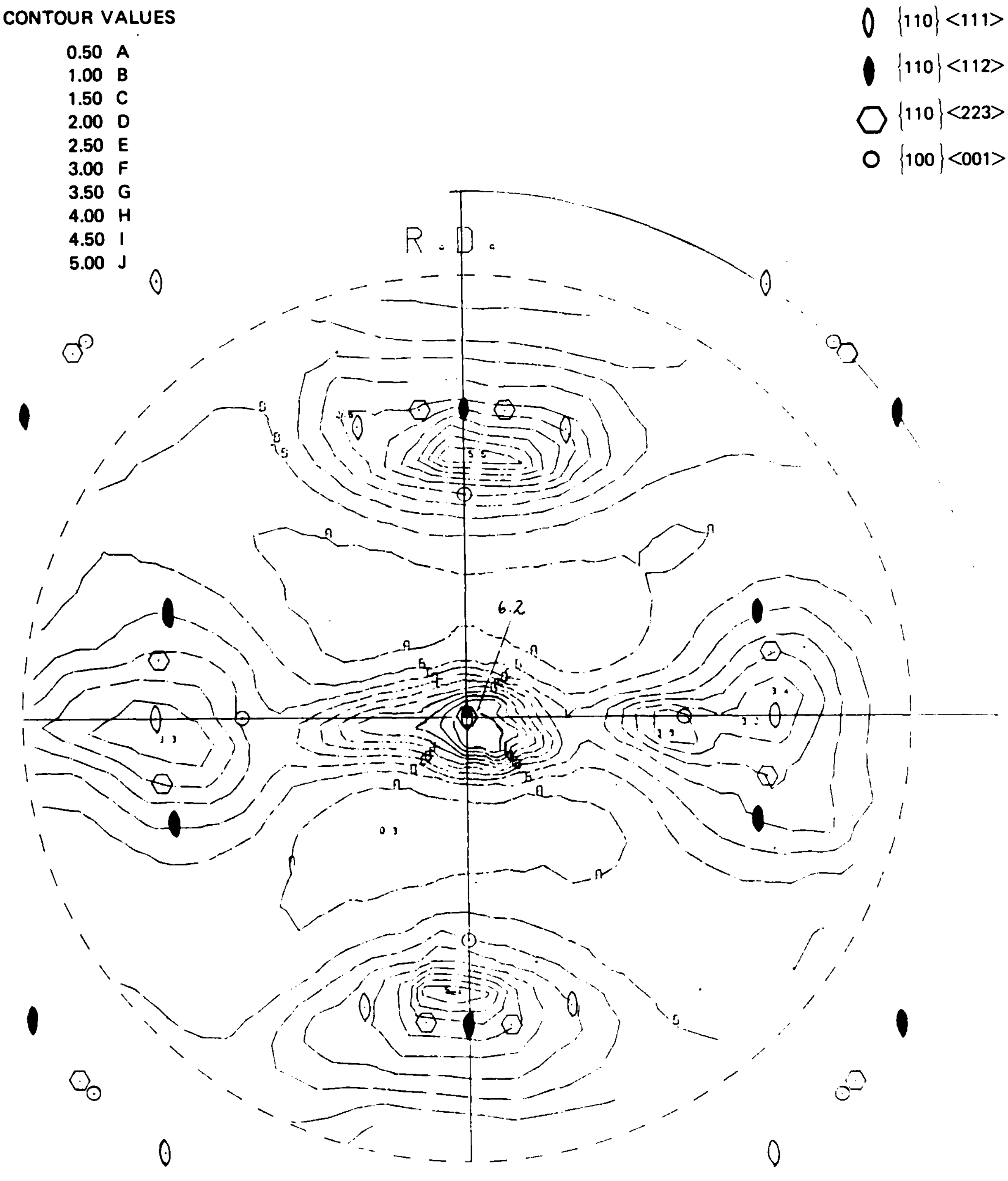


Figure 4a. The (110) pole figure showing texture of the 2-inch-thick plate at the 1/4 T section (0.50 in. below rolling surface). Dotted circle 80° from center of projection.

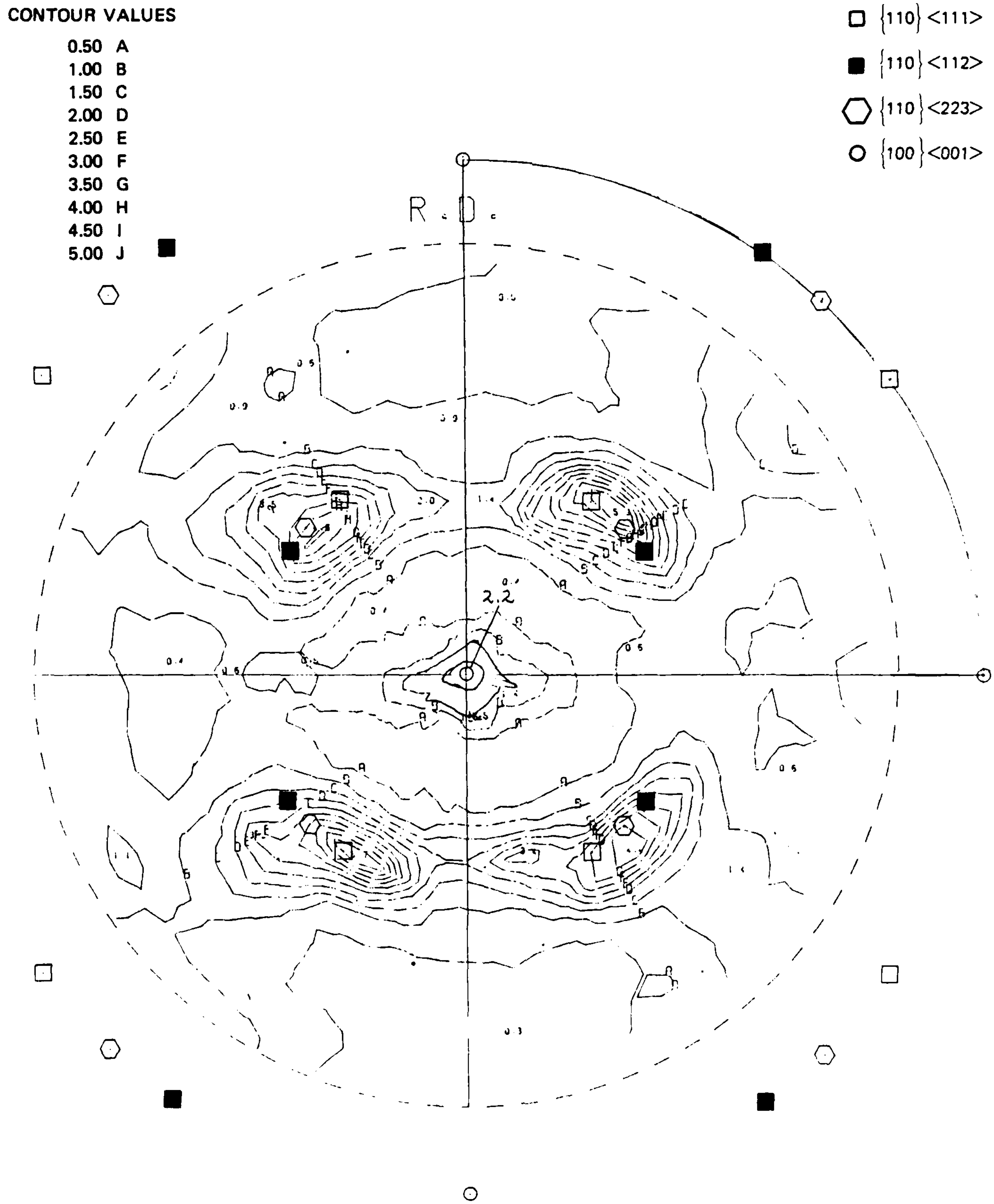


Figure 4b. The (200) pole figure showing texture of the 2-inch-thick plate at the 1/4 T section (0.50 in. below rolling surface). Dotted circle 80° from center of projection.

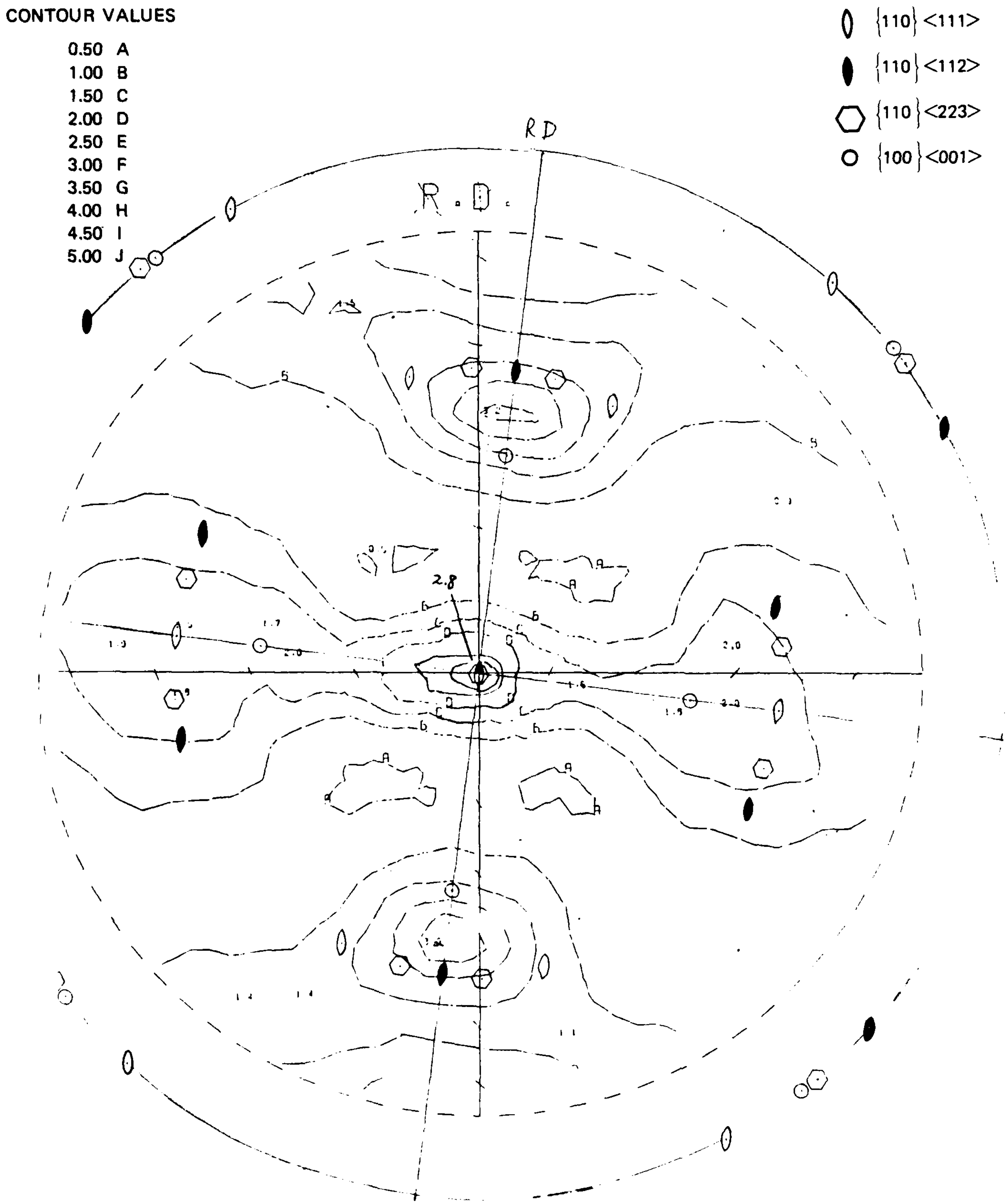


Figure 5a. The (110) pole figure showing texture of the 2-inch-thick plate at the 1/8 T section (0.25 in. below rolling surface). Dotted circle $80^{\circ}$ from center of projection.

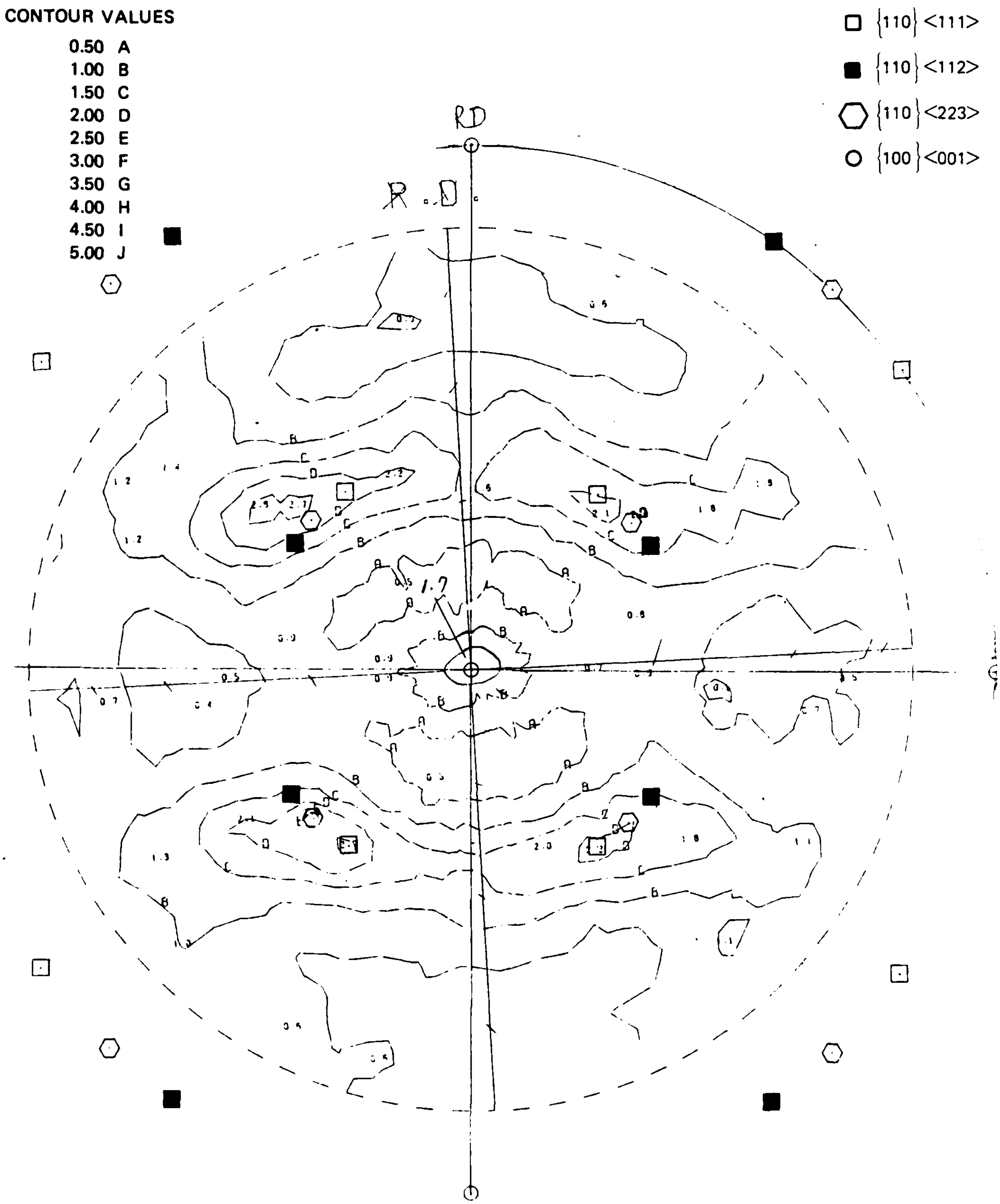


Figure 5b. The (200) pole figure showing texture of the 2-inch-thick plate at the 1/8 T section (0.25 in. below rolling surface). Dotted circle 80° from center of projection.

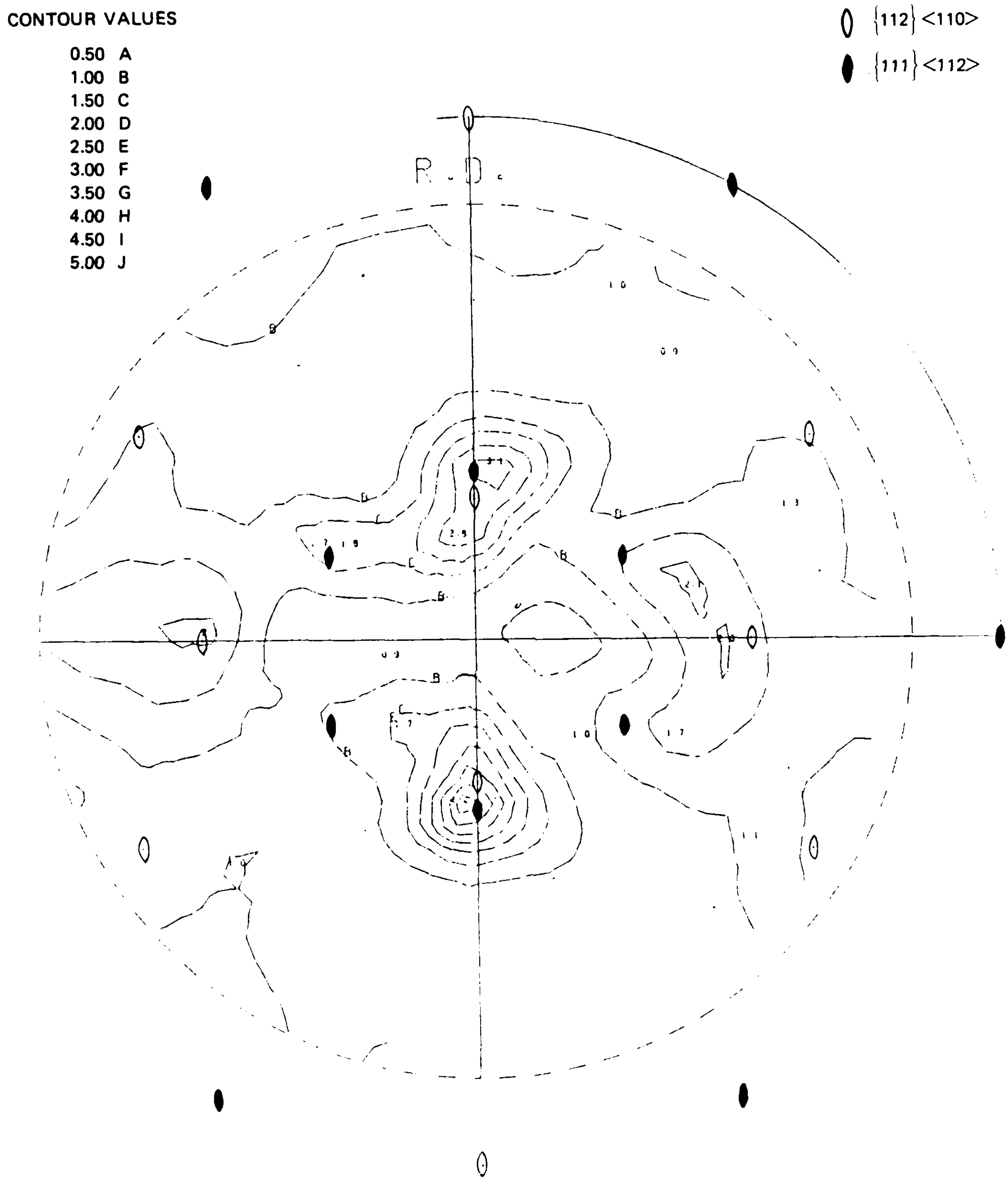


Figure 6. The (110) pole figure showing texture of the 2-inch-thick plate at the 1/16 T section (0.15 in. below rolling surface). Dotted circle $80^{o}$ from center of projection.

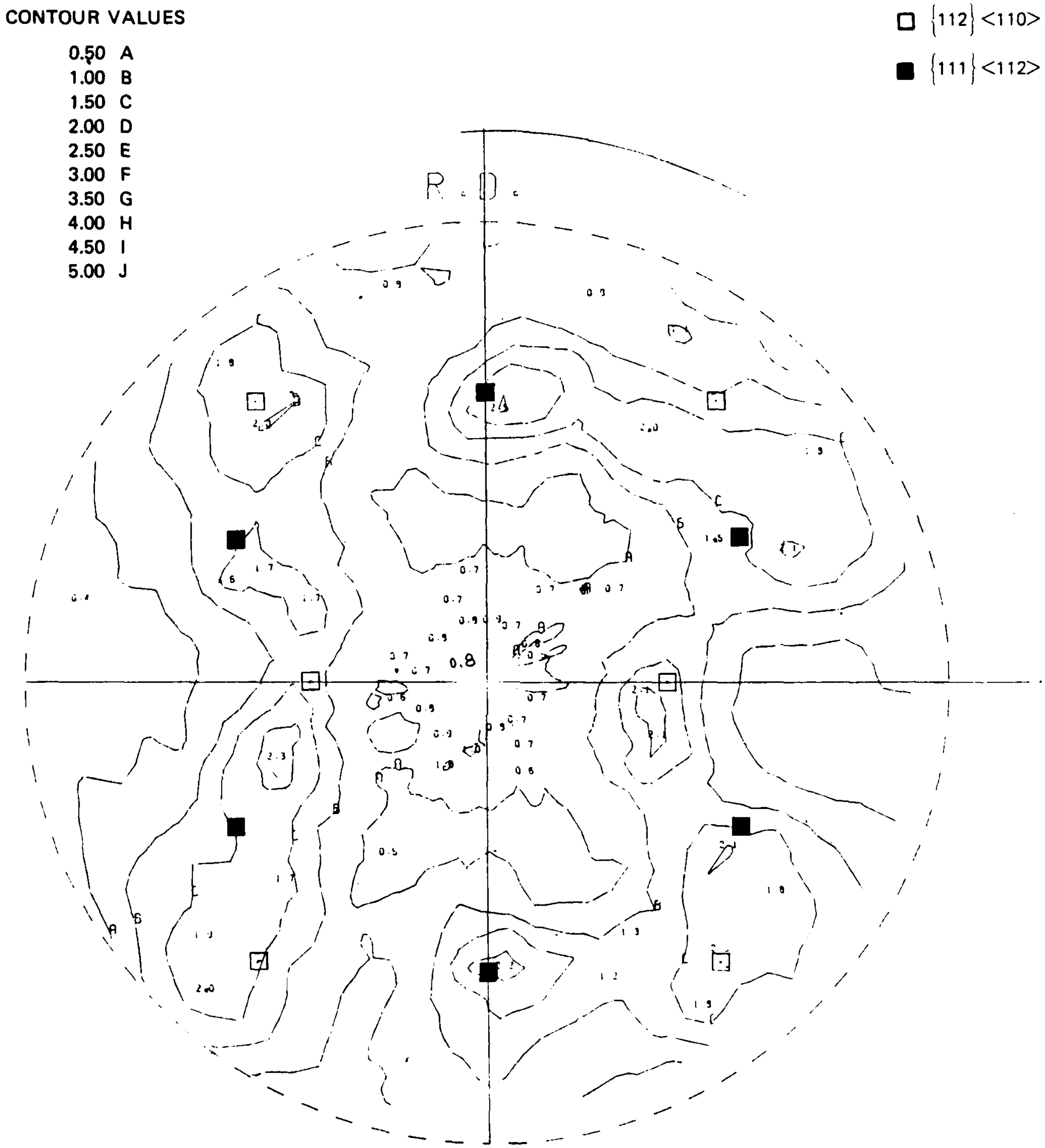


Figure 7. The (200) pole figure showing texture of the 2-inch-thick plate at the 1/18 T section (0.11 in. below rolling surface). Dotted circle 80° from center of projection.

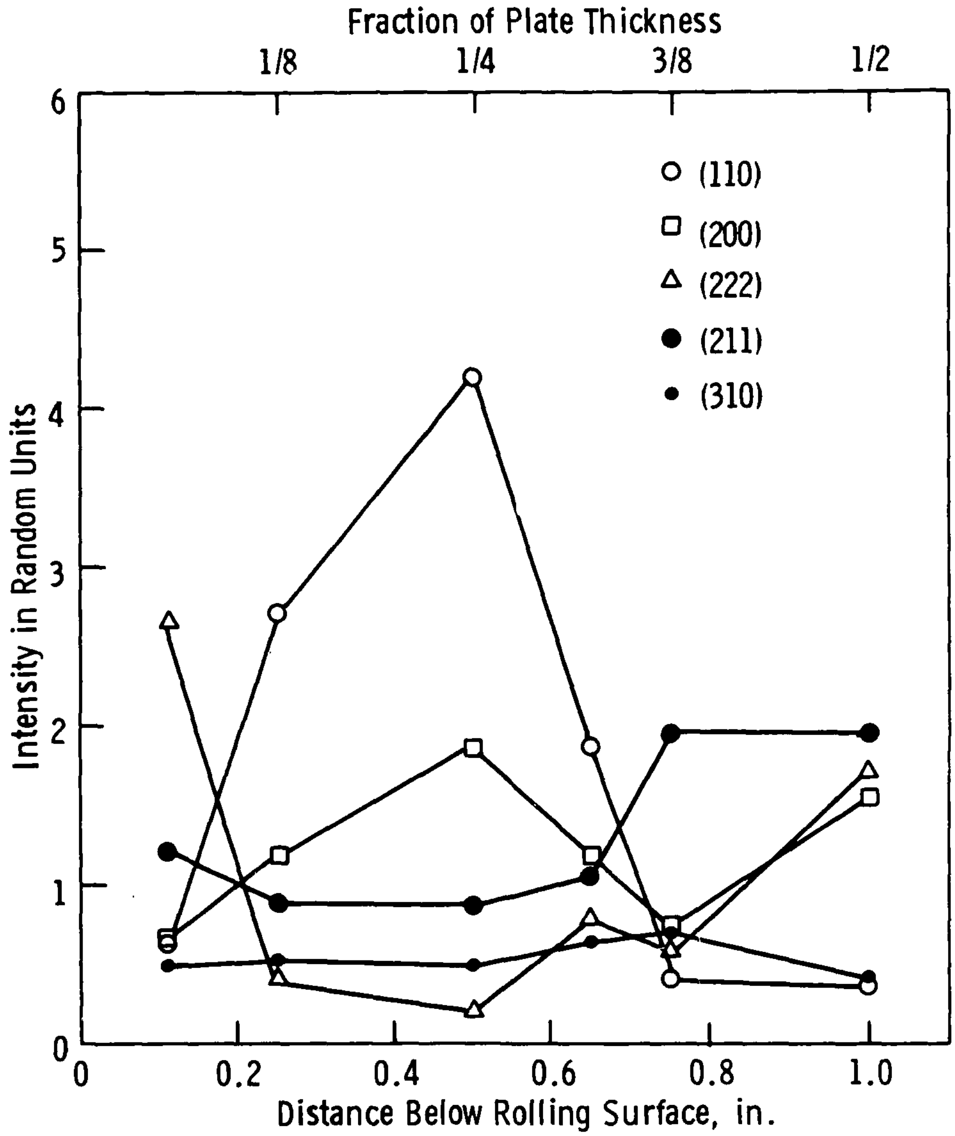


Figure 8. Integrated peak intensity profile in the thickness direction of the 2-inch-thick plate.

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Hsun Hu
Battelle Columbus Laboratories
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Technical Report MTL TR 87-59, November 1987, 24 pp - illus-tables, Contract No. DAAG29-81-D-0100

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The textural variation in the thickness direction of a 2-inch-thick 5 Ni-steel plate, produced by controlled hot-rolling to 90% reduction, immediately water-quenched, then tempered, has been studied. Besides the surface texture, which differs from the interior texture at midthickness only in intensity and in rotational displacement, there is a drastic change in the nature of the texture at the intermediate sections. An analysis of the deformation-zone geometry of the rolling passes indicates that the present observations are consistent with those reported for cold-drawn or cold-rolled strips. The usefulness of this particular texture for textured armor research and future armor development is discussed.

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